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Image Processing and Display of 3D Intra-Coronary Ultrasound Images

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Abstract

Intra-coronary ultrasound provides a means to generate high resolution tomographic images of the coronary artery and surrounding tissue. These images are ideally suited for a number of image processing techniques to improve visualization of the vascular structures of interest. Preliminary results using temporal domain and several anisotropic filters are discussed. A radial gradient filter for boundary detection of the medial-adventitial interface is presented. Multiplanar reformatting and maximum intensity projection displays are also discussed.

Introduction

Coronary angiography is an excellent method to examine the lumen of coronary arteries, but provides little or no information about the vessel wall itself. Postmortem studies suggest that angiography significantly underestimates extent of disease, especially in the early stages of atherosclerosis (1, 2). Methods to determine vessel wall morphology are needed to gain further understanding of the pathogenesis and natural history of coronary atherosclerosis in vivo. Knowledge of the vessel wall may also provide useful information for planning and evaluating the results of acute interventions.

Intra-coronary ultrasound imaging provides a continuous tomographic 2-D echo image of vessel lumen and vessel wall (3). The tomographic images can be stacked to produce a voxel space representation of a segment of a coronary artery over time. Since specular artifacts are variant over time (and space) this provides an opportunity to apply a variety of time domain filters for improved visualization of structures in the image. In addition, the radial nature of the imaging device and the circumferential orientation of the structures of interest suggest that anisotropic filters may be of some benefit for automated boundary detection of vessel walls. Multiplanar reformatting, and 3-D projection displays provide new ways to visually interrogate the image data that may assist in their qualitative and quantitative interpretation. This paper describes the methods and preliminary results of these image processing techniques applied to *in vivo* intra-coronary images.

Methods

Intra-coronary ultrasound was performed in subjects undergoing routine diagnostic coronary angiography, or an intravascular intervention (PTCA, or atherectomy). Images were acquired using a 3.5 F, 64 element, 20 MHz transducer mounted on the tip of similarly sized intra-coronary catheter. Miniaturized integrated circuits located in the tip of the catheter multiplex the incoming signals and transmit them to the host computer where real time dynamic reconstruction using synthetic appeture array methodology is performed. The resulting images are generated and displayed at 10 frames/sec. and stored on Super-VHS tape for subsequent processing and review.

The videotaped images were individually digitized to 512x512x8 bit grey scale images (Videopix, Sun Microsystems), and stored on disk for subsequent image processing using a RISC-based Unix workstation (SPARC I, Sun Microsystems) or a mini-super

computer (Stardent 3000).

Temporal Domain Filters

Two temporal domain filters were employed. The first was a non-linear maximum intensity filter (Figure 1).

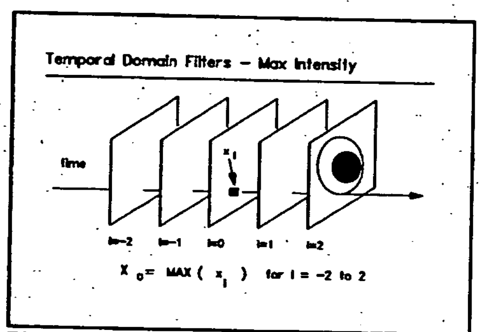

Figure 1. Example of a 5-point maximum intensity filter in the time domain.

This filter fills in specular drop-out and enhances echogenic interfaces that are only intermittently seen in any one frame. Unfortunately it also enhances bright specular artifacts as well. A second temporal domain filter which proved to be more useful was a weighted average time domain filter where the weights conformed to a Gaussian distribution (Figure 2).

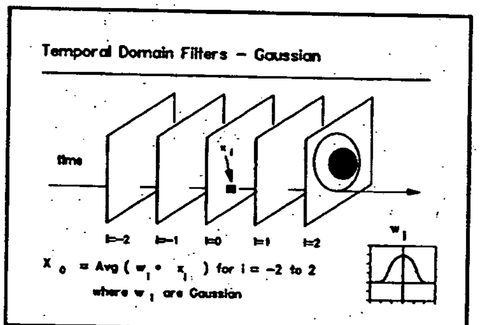

Figure 2. Example of a 5-point gaussian weighted temporal domain filter

Anisotropic Filters

The radial pattern of the ultrasound transmission from the intra-vascular catheter is different from most other imaging modalities which typically originate from an external point of reference. In addition, the vascular structures of interest are circumferentially located around the catheter. These observations suggest that intra-coronary ultrasound may be ideally suited for anisotropic filters whose elements depend on the radial location and distance from the center of the image. Since echo amplitude decreases as it travels through tissue many echo systems employ a time-gain compensation technique to over come the reduction in signal amplitude from tissues far from the transducer (4). A similar technique was devised for use with the intra-coronary ultrasound images (figure 3).

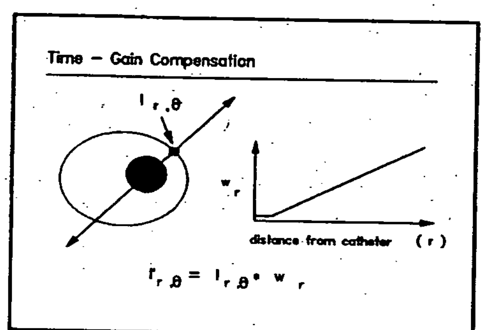

Figure 3. Example of a radial time-gain compensation filter

This filter had the additional benefit of suppressing the very bright echos that inevitably occur when the catheter lies immediately adjacent to the vessel wall.

Another anisotropic filter was devised to facilitate automated boundary detection of the blood-intimal and the medial-adventitial interfaces. The elements of a 7x7 kernel which smooths in the x direction and determines the first derivative in the y direction were rotated according to the following formula:

$$K'_{i,j} = \sin\Theta \cdot K_{i,j} + \cos\Theta \cdot K_{i,j}$$

where K = gradient filter for $\Theta = 0^\circ$

Thus for any point in the image, edges are enhanced in a radial direction from the catheter and smoothing occurs in a circumferential direction around the catheter.

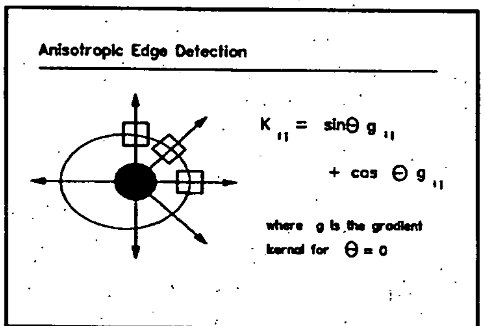

Figure 4. Anisotropic radial gradient filter which smooths in the circumferential direction and determines the gradient in the radial direction.

The resulting radial gradient image is then used for automated boundary detection described in the following section.

Automated Edge Detection

From the radial gradient image an initial approximation of the location of the medial-adventitial boundary can be obtained by choosing the first point from the center along radial line segments with a value above an arbitrarily defined threshold. In some instances this produced an excellent identification of the boundary. However, in other images threshold values were reached significantly inside or outside the boundary of interest or not at all. As a second approximation, a circle was fit to the points by solving the following system of two equations and two unknowns:

$$S_{11} = 2\left(\frac{1}{n}\sum x_i - \frac{\sum x_i^2}{\sum x_i}\right)$$

$$S_{12} = 2\left(\frac{1}{n}\sum y_i - \frac{\sum x_i y_i}{\sum x_i}\right)$$

where S_{11} and S_{12} are the x and y coordinates for the origin of the circle, a third equation (not shown) yields the radius.

The image data from line segments perpendicular to the circle were then remapped to a rectangular cost matrix (Figures 4 and 5). A simulated annealing method will be used to locate the optimal boundary in this matrix.

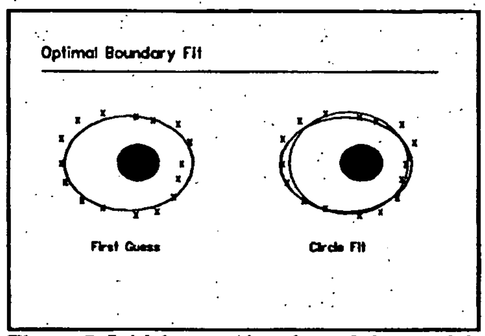

Figure 5. Initial approximation of the medial-adventitial boundary using threshold method in the radial gradient image, and a circle fit to those initial points

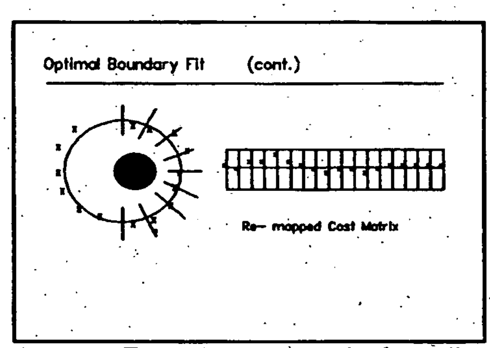

Figure 6. Extracted cost matrix from line segments perpendicular to the circle. Xs represent initial estimation of the boundary points.

Multiplanar Reformatting

The individual processed images were stacked to create a 3-D voxel space. If the image data are obtained while the catheter is stationary, the data illustrate time dependent changes at a single point in the coronary anatomy. If the catheter is being moved in the artery then a 3-D anatomic representation of the vessel segment is possible. Once stacked principle axis multiplanar reformatting allows display if coronal sections of the artery at any angle around the long axis. These projections allow visualization of the lumen and atherosclerotic plaque over several centimeters of an artery.

Angiographic Projections

Using a high speed vector processor maximum intensity projections of the 3-D voxel space can be calculated from any perspective. By choosing a series of incremental perspectives in the x, y or z axis, a maximum intensity cine loop can be generated that has visual attributes of 3-D angiographic display. This allows the viewer to effectively see the entire data set at one time rather than individual slices of the data. With this dynamic display, some structural details of the vessel wall are easier to appreciate than in any single slice.

Conclusion

Image processing offers a number of potential mechanisms to improve visualization of anatomic structures in intra-coronary ultrasound images. Intracoronary ultrasound images are ideally suited for a number of temporal domain and anisotropic filters. Preliminary results from a radially oriented gradient edge operator are promising for detection of the medial-adventitial boundary. Multi-planar reformatting and angiographic projection display methods provide useful means to visually interrogate the 3-D data. These image processing enhancements may provide the means to make significant advances in the study of coronary atherosclerosis and its treatment.

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Index Terms:
3D intra-coronary ultrasound images acoustic imaging anisotropic filters biomedical ultrasonics boundary detection cardiology image data visual interrogation image display image processing maximum intensity projection displays medial-adventitial interface medical diagnostic imaging multiplanar reformatting picture processing radial gradient filter temporal domain 3D intra-coronary ultrasound images acoustic imaging anisotropic filters biomedical ultrasonics boundary detection cardiology image data visual interrogation image display image processing maximum intensity projection displays medial-adventitial interface medical diagnostic imaging multiplanar reformatting picture processing radial gradient filter temporal domain

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